RESULTS FROM ELECTROMAGNETIC MONITORING OF THE Mw 5.1 SAN JUAN BAUTISTA, CALIFORNIA EARTHQUAKE OF 12 AUGUST 1998

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ABSTRACT

Ultra-low frequency (ULF: 0.01-10 Hz) magnetic field anomalies prior to M ≥ 6.9 earthquakes have been reported in various regions of the world. In particular, observations of anomalous ultra-low frequency (ULF) magnetic field variations, not only before but for several months after the 1989 Loma Prieta main shock, motivated the establishment of permanent electromagnetic ULF monitoring stations along the San Andreas Fault. Here we attempt to test whether smaller magnitude earthquakes have associated ULF anomalies using measurements made close to the epicenter of the *Mw* 5.1 August 12, 1998 San Juan Bautista, CA earthquake. In addition, we present scaling calculations that support the hypothesis that a precursory ULF anomaly is related to the size of the earthquake.

The ULF stations, installed and maintained by UC Berkeley and Stanford University, measure 3-components of the magnetic field, 2 components of the electric field, and are co-located with seismometers (which allow us to address the possibility that observed effects, if any, might be attributable to ground motion). The *Mw* 5.1 San Juan Bautista earthquake hypocenter was located 2 km southwest of and 9 km below the EM station, SAO, which was recording continuously at the time. Half-hour spectral averages of the magnetic field data in 9 different frequency bands show no long-term magnetic field anomaly prior to the earthquake. However, closer inspection shows an ~ 0.02 nT increase in activity for two hours prior to the earthquake on all ULF components. Although background noise levels at SAO are of similar magnitude, precluding identification of a precursor, the amplitude of the increase agrees with the order of magnitude estimate of the expected magnetic anomaly prior to the San Juan Bautista earthquake compared with the anomaly observed prior to the Loma Prieta earthquake.

INTRODUCTION

Ultra-low frequency (ULF: 0.01-10 Hz) anomalies in the magnetic fields prior to several M ≥ 6.0 earthquakes have been reported in various regions of the world. In particular, Fraser-Smith et al. (*1990*) recorded anomalous magnetic field fluctuations prior to the 17 October 1989 Loma Prieta *Ms* = 7.1 earthquake in central California (Figure 1) which included an increase in activity about two weeks prior to the main shock that continued until an even larger amplitude increase starting three hours before the main shock. Multiple, but not mutually exclusive, possible physical explanations have been given (*Draganov et al., 1991; Fenoglio et al., 1995; Merzer and Klemperer, 1997*).

Other anomalous ULF signals possibly related to earthquakes were recorded several hours prior to the 7 December 1988 *Ms* = 6.9 Spitak, Armenia earthquake (*Molchanov et al., 1992; Kopytenko et al., 1993*), and further anomalous signals were observed both about two weeks and a few days before the 8 August 1993 *Ms* = 8.0 Guam earthquake (*Hayakawa et al., 1996*). In addition to these observations, the ULF band is worthy of attention because these are the highest frequency signals that can reach the Earth's surface with little attenuation if they are generated at typical California earthquake nucleation depths (~10 km).

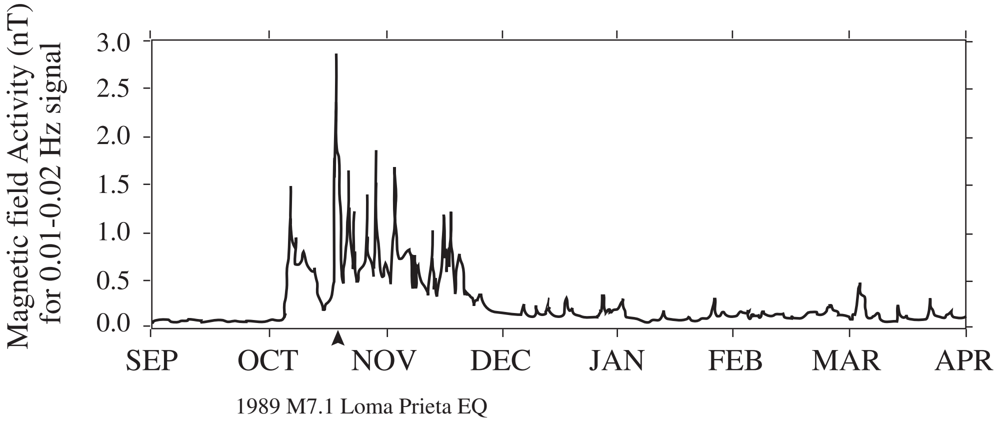

Figure 1. Magnetic field activity from September 1989 through April 1990 measured at Corralitos (COR, see Figure 2), California. The Loma Prieta earthquake occurred on October 17, 1989. (courtesy of *Fenoglio et al., 1993*)

There are fewer reports of ULF anomalies associated with smaller magnitude earthquakes (M ≅ 5) and aftershocks of major earthquakes (*Fenoglio et al.,1993; Park et al.,1993; Kopytenko et al., 2000*). It is unclear whether there is a threshold earthquake magnitude above which ULF anomalies may be produced or whether their detection is directly dependent on the magnitude of the earthquake and distance from the source to the sensor. Molchanov (*personal communication*) suggests that the size (or possibility of observation) of ULF anomalies may scale with the ratio of earthquake magnitude to sensor distance; yet field evidence for this relationship, which may provide further insight into the mechanism producing precursory ULF activity, is lacking. Based on previous observations, if ULF anomalies are associated with M ≅ 5 earthquakes, detection of these anomalies would require surface measurement systems to be very close to the epicenter of the earthquake.

An *Mw* 5.1 earthquake occurred at 1410 UTC on 12 August 1998 on the San Andreas Fault in central California about 2 km southwest of and 9 km below the Hollister, CA, ULF/seismic station SAO, and thereby provided us with the opportunity to test the hypothesis that ULF anomalies are associated with smaller earthquakes. The earthquake was located 12 km south-southeast of San Juan Bautista, at the epicentral coordinates 36.7533° N, 121.4618° W and a depth of 9.2 km (*Uhrhammer et al., 1999*) (Figure 2), and approximately 50 km southeast of the epicenter of the *Ms* 7.1 Loma Prieta

Earthquake in the northern creeping-to-locked transition zone of the San Andreas Fault. SAO is one of 10 permanent electromagnetic ULF monitoring stations established along the San Andreas Fault (Figure 2), and it is operated and maintained by Dr. H.F. Morrison and colleagues at the University of California at Berkeley. At the time of the San Juan Bautista (SJB) earthquake, SAO was fully operational and continuously recording magnetic, electric field, and seismic activity, providing a uniquely complete set of ULF and seismic data from a location very close to a moderate magnitude earthquake.

In this paper we present both the magnetic and electric field data recorded around the time of the San Juan Bautista earthquake. In addition, we use our results to help constrain the relationship between a precursory ULF signal and earthquake size, a relationship which may provide insight into the mechanisms which may produce such anomalous EM fields surrounding earthquakes.

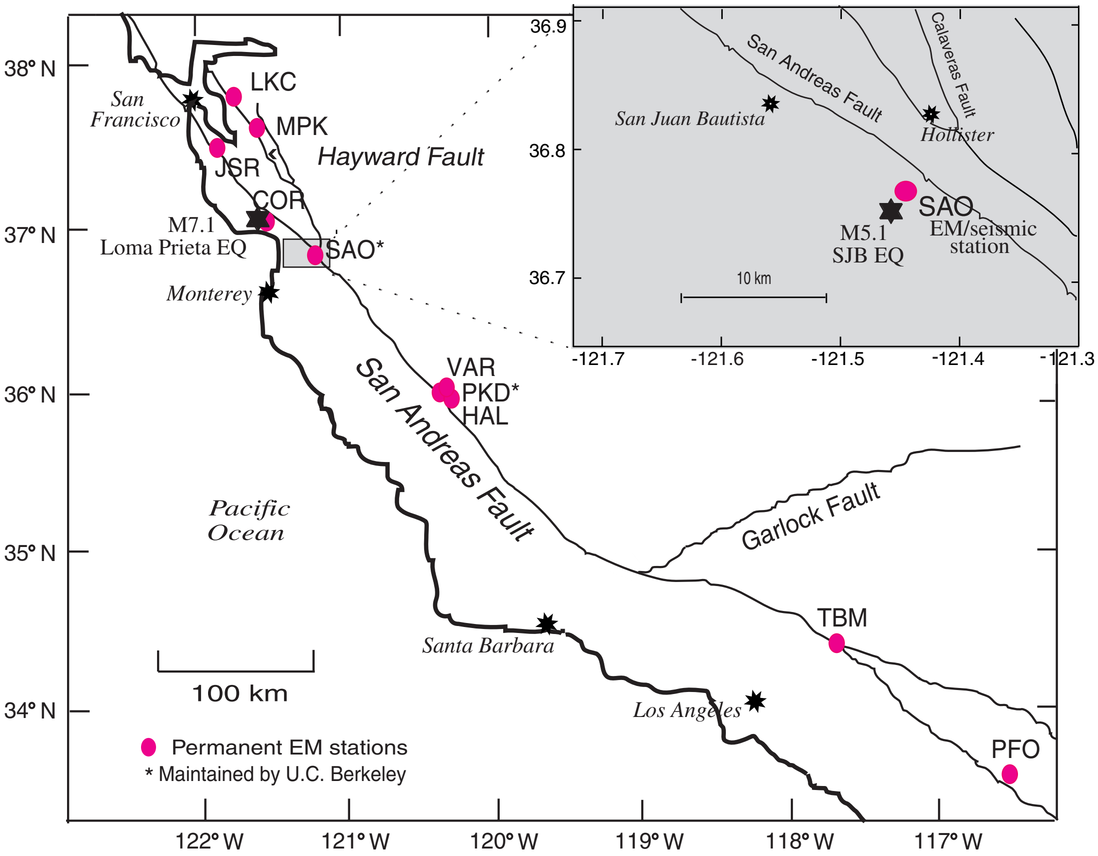

Figure 2. Map showing permanent ULF stations in California. Stations are operated by Stanford University and the University of California, Berkeley. Overlaid is a close-up map of the study area showing the location of the M 5.1 SJB earthquake with respect to the ULF station SAO.

OBSERVATIONS

The SAO ULF station (36.765° N, 121.445° W) is equipped with 3-component magnetic field induction coils (0.0001 - 20 Hz) (manufactured from Electromagnetics Instruments, Inc. (EMI), Richmond, CA, USA) oriented in the geographic east-west, north-south, and vertical directions, and multiple component electric field sensors (DC-20 Hz) utilizing Pb-$PbCl_2$ electrodes. These instruments are collocated with a BDSN (Berkeley Digital Seismic Network) site and utilize the 24-bit Quanterra datalogger and the continuous telemetry connection of the BDSN equipment. The EM field data are recorded at 40 samples/sec, and the waveform data are archived by the Northern California Earthquake Data Center (NCEDC). Further information about the installation, equipment, and noise levels of typical broadband seismic and ULF stations of this sort are detailed by *Uhrhammer et al. (1998)* and *Karakelian et al. (2000).*

Figure 3 shows east-west component (Hx) magnetic field data recorded at SAO during August, 1998, and the same 31 days of data recorded at a remote reference site PKD located in Parkfield, CA, approximately 130 km distant (see Figure 2). Half-hourly power spectrum averages (MA indices) (*Bernardi et al., 1989*) in 13 different frequency bands covering the range 0.0056 - 10 Hz were calculated to show the variation of magnetic field activity before and after the 8/12/98 earthquake. Comparison of SAO data with the PKD data show that the predominant component of the magnetic fluctuations evident in these records represents natural geomagnetic variations generated in the upper atmosphere and above. On close comparison, the two MA index records are nearly identical and any local signals, either cultural or tectonic in origin, are concealed in this natural activity. A spike in the higher frequency SAO data at the time of the earthquake is due to ground motion causing movement of the magnetic field sensor through the Earth's magnetic field.

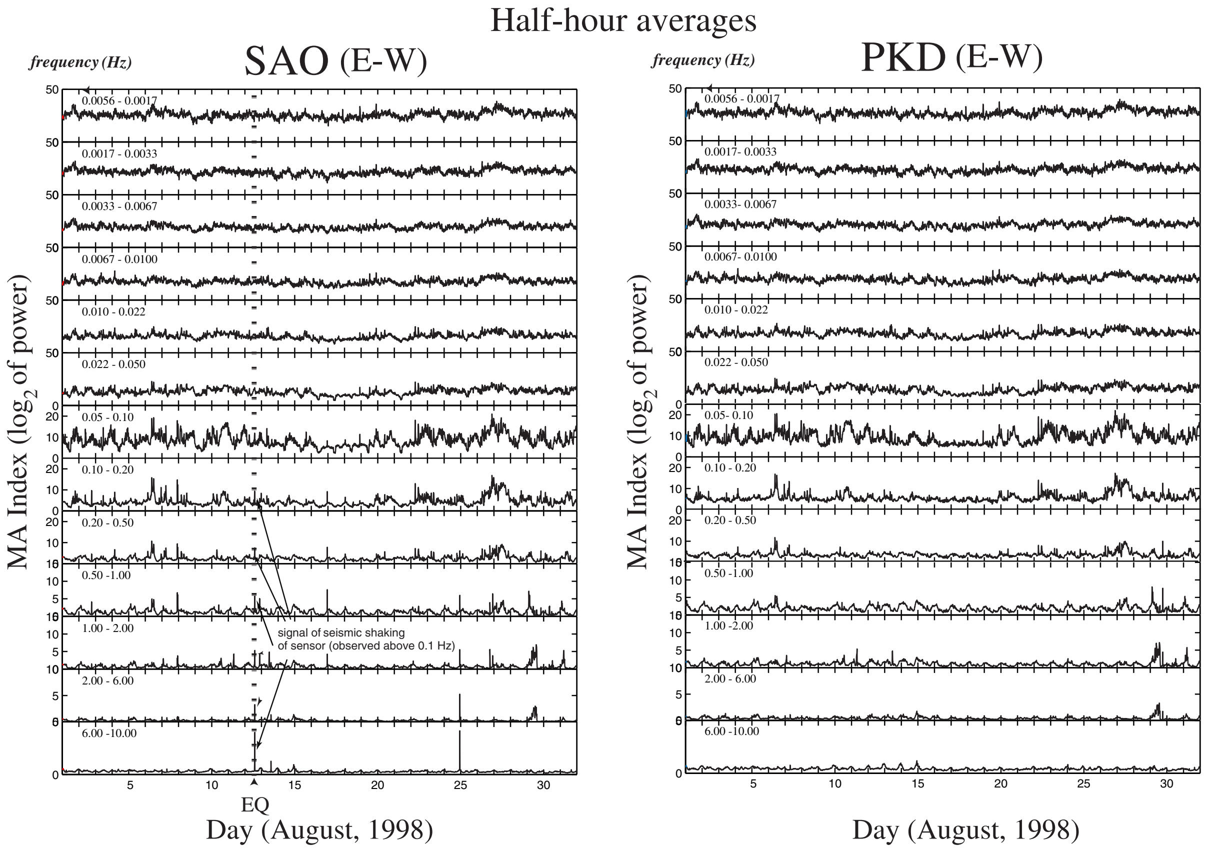

Figure 3. MA Indices for the E-W magnetic field component for the month of August at SAO and a remote station PKD. MA indices are a set of logarithms to the base two of the half-hourly averages of the power in 13 frequency bands covering the overall range from 0.01- 10 Hz. (data courtesy of the Northern California Earthquake Data Center and the Seismological Laboratory at UC Berkeley). The occurrence time of the SJB earthquake is indicated in the SAO record.

Since the magnetic indices shown in Figure 3 are half-hour averages, which have the potential to mask small short-term changes, we next inspected the original magnetic and electric field measurements several hours prior to the earthquake. Figure 4 shows one minute averages of the absolute value of the data in the 0.01-0.02 Hz frequency band about six hours prior to the earthquake. These data show an obvious increase in activity on all components beginning about 3 hours prior to the main shock. The increase in magnetic field activity is more pronounced on the horizontal components than on the vertical component compared to the normal background noise level of 0.01-0.02 nT, and is also much more pronounced than at higher frequencies between 0.5-1.0 Hz (not shown). Both observations are those anticipated for a source at the hypocentral depth of 9 km; the component sensitivity probably reflects the higher sensitivity of the horizontal components to low-frequency ionospheric disturbances (*Karakelian et al., 2000*), whereas the frequency sensitivity can be explained by the "skin depth effect" where higher frequencies traveling through the Earth are attenuated more than lower frequencies

(*Telford, et al., 1990*). The increase in ULF activity in Figure 4 also peaks at the time of the earthquake and then returns back to normal background level about three hours later on all components. Consequently, it could be related to the upcoming seismic event, even though the amplitude of the increase is comparable to increases due to random noise observed in the data at other times (see Figure 5).

Figure 5 shows a similar increase in magnetic field activity a few hours prior to the earthquake at the remote station PKD, indicating that this increase is likely due at least in part to natural atmospheric activity. There is a small increase, however, in the subtracted data (Figure 5C) that may be an indication of local activity at SAO, although the increase is small compared to the background noise level at SAO. In addition, Figure 5D shows that similar increases in the subtracted data at other times are common. We conclude that we cannot state whether or not a precursor occurred, but that any precursor was less than 25 pT in the 0.01-0.02 Hz range.

SCALING CALCULATIONS

Based on reports of previous ULF anomalies before M ≥ 6 earthquakes and the lack of any obvious precursor (electromagnetic or other) for this *Mw* 5.1 earthquake, we assume that electromagnetic precursors are related to the size of the earthquake. Because precursory magnetic fields are likely due to fluids in the fault zone (*Draganov et al.,1991; Fenoglio et al., 1995; Merzer and Klemperer, 1997*), we choose as an initial assumption that such fields are related to the volume of the earthquake rupture zone in which such fluids might exist and have participated in the earthquake preparation phase.

Based on this assumption, we can make an order of magnitude estimate of the amplitude of the magnetic anomaly expected prior to the *Mw* 5.1 SJB earthquake compared to the maximum anomaly of 5 nT observed in the 0.01-0.02 Hz band 3 hours prior to the *Ms* 7.1

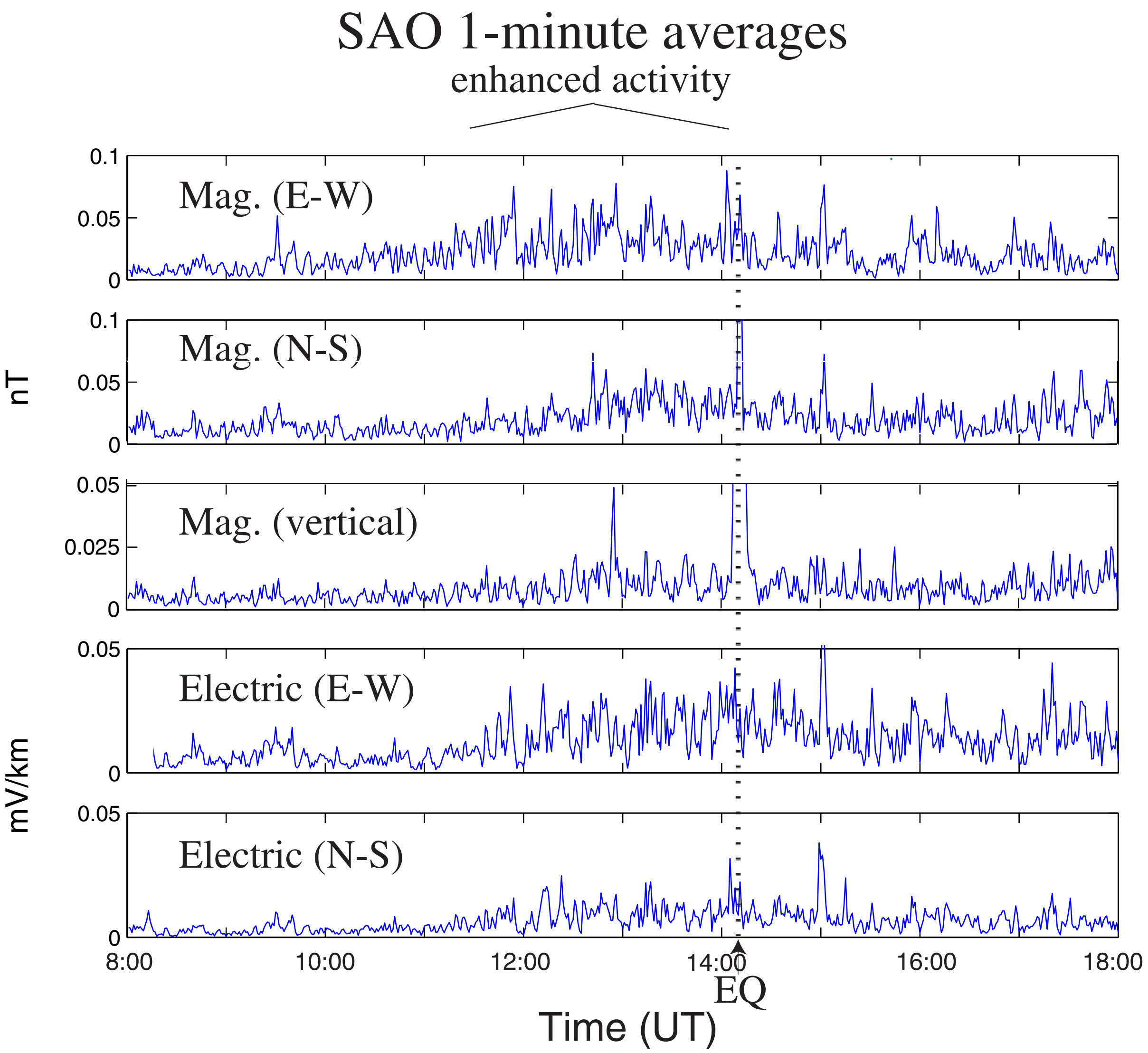

Figure 4. Multiple component ULF activity at 0.01-0.02 Hz recorded at SAO. Data are one-minute averages of the absolute value of magnetic and electric field amplitudes. The occurrence time of the SJB earthquake is indicated. Shaking of the instruments due to passage of the seismic wave occurs within seconds of the earthquake occurrence.

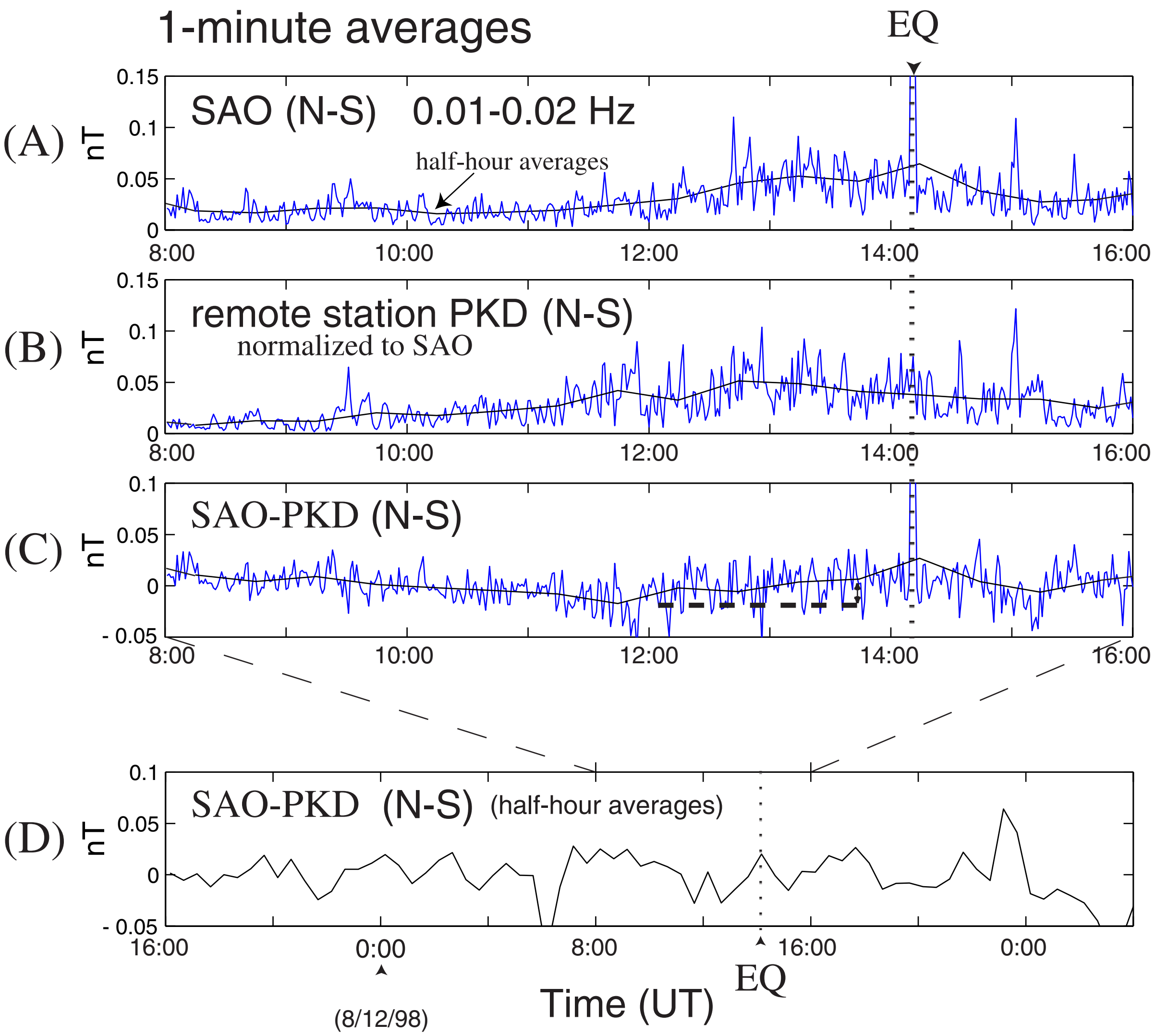

Figure 5. Magnetic field data recorded on the N-S magnetic field component at both SAO and a remote station PKD. Data in panels A,B, and C are one-minute averages of the absolute value of the magnetic field amplitude at 0.01-0.02 Hz. PKD data are normalized to SAO by multiplying by mean_{SAO} / mean_{PKD} (means were calculated over the 8 hour interval shown). Overlaid in a solid line are half-hour averages to show overall trend in data. Dashed line in panel C shows the increase in the differenced data. Panel D shows half-hour averages of differenced magnetic field data for over 36 hours. Diurnal variations in the averages in panel D were removed by high pass filtering frequencies shorter than 12 hours. The occurrence time of the SJB earthquake is indicated.

Loma Prieta earthquake (*Fraser-Smith et al., 1993*). The seismic moment of an earthquake, M_o, is defined as

$$M_o=\mu\Delta\upsilon S \tag{1}$$

where μ is the shear modulus, $\Delta\upsilon$ is the slip on the fault plane, and S is the area of the fault plane (*Udias, 1999*). The stress drop of an earthquake is given by

$$\Delta\sigma=C\mu\Delta\upsilon/r \tag{2}$$

where C is constant related to the shape of the fracture and r is the length dimension of the fault plane (*Udias, 1999*). Using equations (1) and (2), we can solve for the stress drop in terms of the seismic moment:

$$\Delta\sigma=C\ M_o\ /rS. \tag{3}$$

The volume dimension of the rupture zone, V, can be roughly estimated as

$$V=(rS)^{2/3}\Delta x \tag{4}$$

where Δx represents the width of the fault zone. We can rewrite equation (4) in terms of the seismic moment and stress drop as

$$V \cong (CM_o/\Delta\sigma)^{2/3}\Delta x. \tag{5}$$

Next, we assume the same fracture-shape constant C and stress drop $\Delta\sigma$ [50 bars: *Kanamori and Satake, 1996*], for both the Loma Prieta (LP) and SJB earthquakes. The hypothesis that the stress drop is approximately constant for all earthquakes has been confirmed empirically by Kanamori and Anderson (*1975*). Hence

$$V \cong M_o^{2/3}\Delta x. \tag{6}$$

We determine the width of the fault zone, Δx, from the aftershock distribution of each earthquake. For Loma Prieta, we use a range of 3-4 km (*McNally et al., 1996*), and for SJB we use the range 0.08-0.5 km (*J. McGuire and G. Beroza, personal communication*). The appropriate seismic moments are $3\text{x}10^{19}$ N-m (*Kanamori and Satake, 1996*) and $5.32\text{x}10^{16}$ N-m (*Uhrhammer et al., 1999*) respectively. We note also that *Beroza and Ellsworth (1996)* claim that the size and duration of the initial, low moment-rate preparation phase of an earthquake, termed the nucleation phase, scales with the total seismic moment of the earthquake, suggesting that this preparation process carries information about the eventual size of the earthquake. Independent of the exact generation mechanism of precursory ULF signals, it is likely that short-term ULF signals if any are produced during this nucleation phase and are likewise related to the seismic moment of the main shock.

Finally, we assume that the precursory magnetic field is produced at the hypocentral depth of the earthquake. The attenuation of electromagnetic fields generated by electric- or magnetic-dipole sources submerged in a conducting medium is characterized by the skin depth, δ, defined as

$$\delta = (\pi f \mu \sigma)^{-1/2} \qquad (7)$$

where f is the frequency, μ is the permeability of the medium (we use the permeability of free space, μ_o, where $\mu_o = 4\pi \times 10^{-7}$ H/m), and σ is the electrical conductivity (*Telford, et al., 1990*). This skin depth is the measure of distance over which the amplitude of the wave is attenuated to 1/*e* of its original value. Considering the epicenters of both the LP and SJB earthquakes were within 7 km of the recording instruments, and that there is minimum attenuation of the electromagnetic waves when they propagate along the surface of the earth (*Bubenik and Fraser-Smith, 1979*), we use the hypocentral depths (17 km for LP (*Dietz and Ellsworth, 1990*) and 9.2 km for SJB (*Uhrhammer et al., 1999*)) in our calculations. Using appropriate crustal conductivities of 0.01 S/m (*Unsworth et al., 1997; M. Unsworth, personal communication*), we calculate the magnetic field at the hypocenter of the LP earthquake to be 7 nT, in order to produce the 5 nT observed at the EM station COR. We will estimate the largest magnetic anomaly at SJB if we use the maximum value of $\Delta x_{SJB} = 0.5$ km and the minimum value of $\Delta x_{LP} = 3$ km. Using skin depth calculations, the above values yield a maximum expected magnetic anomaly prior to the SJB earthquake of only 0.015 nT at 0.01-0.02 Hz, corresponding to a field at the hypocenter of 0.017 nT.

A 0.015 nT anomaly is on the order of the increase observed in the subtracted data shown in Figure 5C, but of course 0.015 nT is less than the noise level measured at SAO (Figure 5D). However, our observations are consistent with the hypothesis that any magnetic field anomaly scales with the volume of the earthquake rupture zone, and hence is related to the seismic moment.

It is important to keep in mind that because of varying physical properties of faults, we do not necessarily expect to observe similar precursory signals for all earthquakes. Yet, we can use these physical properties along with our observations to further constrain the mechanism by which a ULF precursor is produced. For example, one proposed mechanism is the electrokinetic effect (*Ishido and Mizutani, 1981; Fenoglio et al., 1995*). Electrokinetic effects are the electrical currents (and magnetic fields) generated by fluid flow through the crust in the presence of an electrified interface at the solid-liquid boundaries. In this process, the current produced and fluid flow are coupled so it is important to define this fluid flow as well as possible. Information about the fluid content, pressure changes, and, consequently, overall volume of crust that is being effected are important. If we know this volume dimension from our above analysis, this can help determine whether the electrokinetic effect is a viable mechanism for producing expected magnetic anomalies. Exploring and constraining various mechanisms such as the electrokinetic effect is an important next step in understanding electromagnetic signals associated with earthquakes

In conclusion, because EM stations cannot be significantly quieter and because ULF skin depth attenuation is minor for crustal earthquakes, we need to focus on earthquakes with $M > 6$. It may at present be impossible to test whether earthquakes with $M \leq 5$ have associated magnetic anomalies of the Loma Prieta type.

ACKNOWLEDGMENTS

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Discussion:

Greg Beroza (Stanford U.): How much of a difference does the shallower depth of the San Juan Bautista earthquake have on electromagnetic signals compared to the deeper depth of the Loma Prieta?

Darcy Karakelian: Not so much difference because we are interested in a 0.01 Hz signal, a very low frequency at which you don't get that much attenuation. The depth did contribute to skin depth calculations, but not by a lot.

Bill Bakun (USGS, M.P.): How close does your sensor have to be to an earthquake?

Darcy Karakelian: People have done modeling in the past and it is believed that for a magnitude 6 or greater earthquake, you should be within 60 km, for ultra-low frequency waves. For Loma Prieta, it was modeled that you could see it no further than about 7 skin depths. At 0.01 Hz, that is probably no more than 100 km.

Ramon Arrowsmith (Arizona S.U.): What is the source of the EM signal in the Earth?

Darcy Karakelian: Good question. A lot of research is being done on the generation mechanism. Piezomagnetism is one mechanism. The electro-kinetic effect is another: pore pressure changes cause a conductive fluid flow that causes a current and related magnetic field. The Loma Prieta anomaly continued for about 6 months after the main shock, so whether the same mechanism occurred before and after we don't know, and whether the signals we saw after the earthquake are precursors to the aftershocks or an effect of the main shock is unclear.

Walter Mooney (USGS, M.P.): It seems that there are not enough stations currently. Do you agree that this hampers your research?

Darcy Karakelian: Absolutely. The distribution of stations in California is not dense enough. We need more!